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Comparative evaluation of existing and innovative rail–road freight transport terminals

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Abstract

The paper evaluates technical and logistics developments that could lead to increased economic and technical efficiency of rail–road transport terminals. The main design parameters are identified (length and utilisation of transhipment tracks, train and truck arrival behaviour/patterns, type and number of handling equipment, mean stacking height in the storage area, terminal access system and procedures) and analysed. A comparative evaluation of selected conventional and advanced technologies is performed by use of an analysis tool that was developed on purpose. This tool consists of three modules (an expert system, a simulation model and a cost calculation module). The overall outcome of the analysis is a number of cost-versus-volume curves for various terminal configurations. The paper concludes with two groups of results: (a) a comparative evaluation of conventional and advanced technologies that reveals similarities in terms of track numbers and the associated area requirements as well as differences in terms of layout flexibility, number of equipment, stacking policies and personnel requirements. Each design is proved effective for a certain cargo volume range. (b) A critical assessment of terminal capacity issues. It is identified that the capacity limitations are imposed mainly by the sidings/transhipment track sub-system rather than by the handling equipment. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Rail–road freight transport terminals; Conventional/innovative handling equipment; Expert systems; Simulation

1. Introduction

Intermodal transport in Europe has registered a high rate of growth for many years since the beginning of its services. This growth is partly due to systematic promotion and subsidies received

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in various EU countries. Moreover, a significant part of the market consists of traffic attracted from conventional rail rather than from road. In this context it is worth mentioning that in the most recent years, the growth trends of the past were not confirmed, and clear trends for the future are not self-evident (EC/DG Transport, 1997a, 1999a).

This paper is related to a recent research study aiming to introduce and recommend technical and logistics developments that could lead to increased economic, managerial and technical efficiency of intermodal transport. The study consists of a series of complementary parts designed to analyse requirements for integrated terminals and rolling stock in relation to market forces, transport modes, intermodal transport units, advanced intermodal terminal technology (including tests and demonstrations of pilot equipment), trunk haul production forms and Trans-European network effects. The analysis has been supported by three models: a macro-model for the analysis of transport chain, an analytical model for pre- and post-haulage sub-systems and a micro-model for the comparative evaluation of alternative terminal designs (EC/DG Transport, 1999a).

Intermodal transport terminals can be classified into different categories according to cargo volume, terminal location/access, handling equipment used, types of mode served, etc. (EC/DG VII, 1995; Wiegmans et al., 1999). Comparative evaluation of alternative terminal designs (using conventional technologies) has been performed well in advance (Lacey, 1980; Erwin, 1983; Derry, 1984) as well as in the following years (Ferreira and Sigut, 1993; SNCF, 1998) while selected issues (space or equipment optimisation) have been further investigated (Taleb-Ibrahimi et al., 1993; Ferreira and Sigut, 1995). In recent years, new innovative equipment appeared (see Woxenius, 1997). The comparative evaluation of this equipment was performed mainly through research projects (EC/DG VII, 1995, 1997a,b, 1999a; EC/DG TREN, 2000) while specific issues have been thoroughly analysed (Krishnamurthy et al., 1993; Bostel and Dejax, 1998). The scope of this paper is to present the parameters affecting rail–road terminal design as well as to present the analysis tool and the results from the comparative evaluation of selected conventional and innovative terminal configurations. This tool contains three basic components: An expert system to “produce” the alternative designs, a simulation model to test the equipment adequacy and identify the truck waiting/service times and finally a cost calculation module. Issues related to market analysis, network effects, pre- and post-haulage organisational schemes and transport chain structure/results are left out of the present investigation.

The rail–road terminal has been approached from a specific angle, aiming mainly at the identification of the effects that advanced technologies and advanced rail operation can have on pertinent criteria including cost, cost-effectiveness as well as interoperability, availability and reliability.

In Section 2 the main parameters affecting the design of a rail–road terminal are analysed in a way that basically fits the needs of the modelling approach which is described in Section 3. The criteria on which the comparative evaluation of conventional and advanced technologies is based are also described in Section 3. The paper concludes with results of the analysis and a critical assessment of these results.

2. Identification of the terminal design parameters

The rail–road terminals provide the space, the equipment and the operational environment for transferring intermodal transport units (ITUs) between the different transport modes. Rail–road terminals consist of a wide range of installations, ranging from simple terminals providing transfer between two or three modes of transport, to more extensive centres providing a number of value-added services such as storage, empties depot, maintenance, repair, etc. The requirements concerning terminal operation are increased by those corresponding to scheduled trains, train-to-train transhipments, increasing number of clients (private railways, intermodal operators) and complexity of data in the freight nodes (customs, hazardous goods) (Sondermann and Ballis, 1999). A typical rail–road terminal includes the following elements:

(a) rail sidings for train/wagon storage, marshalling and inspection purposes,
(b) transhipment tracks (also termed loading tracks) for the train loading/unloading operations,
(c) storage or buffer lanes for ITUs,
(d) loading and driving lanes for the trucks, and
(e) gates, internal road network.

In the simplest type of operation, the train arrives on the transhipment line, is serviced (unloaded and/or loaded) and remains there until departure. This simplest type of operation enables almost exclusive direct transhipment between wagon and trucks without intermediate storage on the ground. The unloading and loading sequence is dictated mainly by the truck arrivals at the terminal (Bose, 1983).

Real-life operations are generally more complicated: If the number of incoming wagons per train exceeds the length of the track, the train has to be shared out over two (or more) tracks. Moreover, if the number of incoming trains (or train parts) exceeds the capacity of the transhipment tracks, certain trains have to be removed from the transhipment tracks after an unloading/loading phase of a few hours, in order to make space for new inbound trains. This procedure requires that the first pulse of wagons be completely unloaded, either onto the trucks or into the buffer lanes, in order to guarantee the availability of ITUs for customers. The empty wagons are then transferred to storage sidings and the next pulse of wagons can be marshalled into the transhipment tracks. After that the empty wagons are composed to form the outgoing trains. A wagon pin adjustment procedure prepares the wagons to accommodate the new loading units. After the wagon's loading and the necessary inspections and brake tests, the train is ready to depart.

The typical rail–road terminal is a complex system where many parameters are strongly interrelated. Parameters like the terminal's location in relation to the spatial allocation of production and consumption centres, the existence of antagonistic terminals, the access to the major rail and road networks, etc. significantly affects the cargo volume and the ITU mixture served. Other parameters like the cost and availability of land are determined mainly by local conditions (Staley, 1983). On the contrary, a number of parameters are determined by the terminal planner (or imposed by the terminal authorities) and play a dominant role since they outline the terminal layout and determine its limits and productivity (Ballis, 1999). Taking into account the existing situation in Europe, the following basic design parameters can be distinguished:

(a) length of transhipment tracks,
(b) utilisation of transhipment tracks,
(c) train and truck arrival behaviour/patterns,
(d) type and number of handling equipment,

(e) mean stacking height in the storage area, and
(f) terminal access system (mainly rail side) and procedures.

The context of each of the above parameters is analysed below.

2.1. Length of transhipment tracks

The length of transhipment tracks affects both terminal dimensions and everyday operations. It is determined by three factors: the train length, the land availability and cost constraints.

Real-world considerations impose limitations on train length according to specific operating conditions (e.g., safety against derailment). Limitations may also be imposed by mountainous landscape or the length of passing tracks (e.g., for trains to and from Italy). The "long" European trains have a length of 600–750 m.

The land availability constraints are explained by historical reasons: When the first- and second generation terminals (i.e., the majority of existing terminals) were built, many European managers thought that combined transport had no future. Combined transport represented a marginal percentage of the total, and its growth rate was lower than it is today. There was neither political incentive to promote combined transport nor such willingness from the side of the operators. This in turn explains the low level of investment in such terminals and the lack of willingness to provide terminals with really efficient equipment and ideal locations (EC/DG Transport, 1999b).

2.2. Utilisation of the transhipment tracks

The term "transhipment track" characterises a rail track that can be served by the terminal handling equipment (e.g., a rail track under the legs of a gantry crane). On the contrary, a "waiting track" enables only the train dwell in the terminal. Fig. 1 presents a module of a transhipment terminal where four transhipment and two waiting tracks are identified. This module represents a best-practice configuration according to the German railways experience.

The utilisation of the transhipment tracks is expressed in the rail sector by the terms "static" and "dynamic" terminal capacity. "Static capacity" assumes that two trains are served per track per day (one incoming in the morning and one outgoing in the evening). "Dynamic capacity" assumes that more than two trains can be accommodated per day on a given loading track. This means that the terminal's handling equipment serve more trains but on the other hand, trains need to be switched between transhipment and waiting tracks and therefore the (above mentioned) "clear the train" operation is required. Conclusively, there are three effects due to "dynamic capacity" operation: Additional effort for switching the trains (shunting locomotive and personnel involved), additional effort for the handling equipment and truck delays because the handling equipment are used in parallel for truck service and "clear the train" operations.

2.3. Train/truck arrival patterns

In a scheduled-responsive railway operation structure, train movements are regulated with respect to a pre-established and conflict-free schedule (Sahin, 1999). The train arrival patterns in

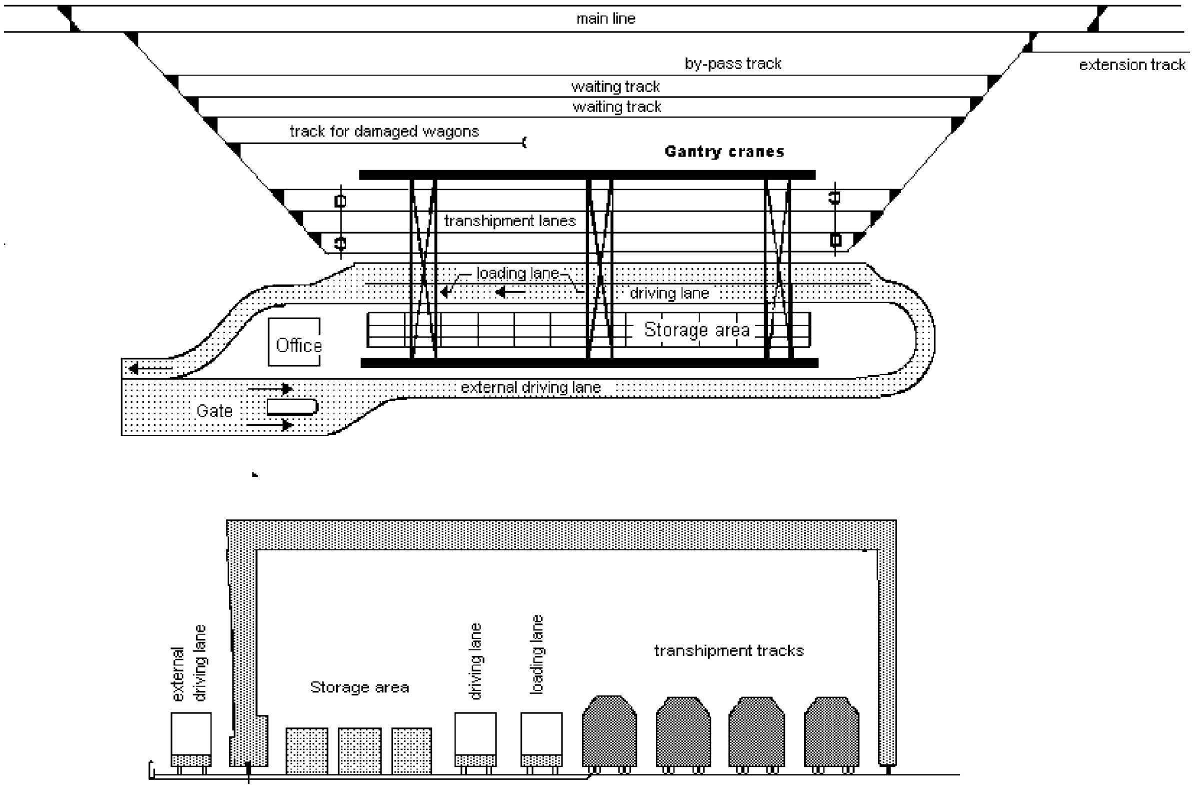

Fig. 1. Layout and cross-section of rail–road terminal equipped with three gantry cranes.

the terminals are dictated by the organisational structure of the whole network. The vast majority of the European network accommodate passenger and cargo trains, that due to their low (relatively to passenger train) speed, reduce disproportionately the network capacity in mixed circulation. For that reason, the commercial trains travel usually overnight and are served during the day. As a result of this policy, the majority of trains arrive in the terminals during the morning and leave in the evening.

Truck arrival patterns are determined by the train timetable, the terminal working hours and by the market conveniences. The organisation of roadside activities plays an important role in determining terminal capacity and performance. Fig. 2 shows typical train unloading/loading operations according to lorry arrival patterns. Four phases can be distinguished.

The first phase starts when the unloading operations start, usually following arrival of the train or after the terminal opens (in the case of trains arriving at night). In general, a significant number of trucks are already present and the unloading operations are concentrated in servicing these trucks. During this phase, direct transhipments from wagon to truck are carried out. After some time, truck arrival rate falls and the handling equipment is using the idle times to tranship load units to the storage area. This second phase is a mixture of direct unloading from train to truck and indirect transhipments (wagon to storage and storage to truck). The third phase is pure

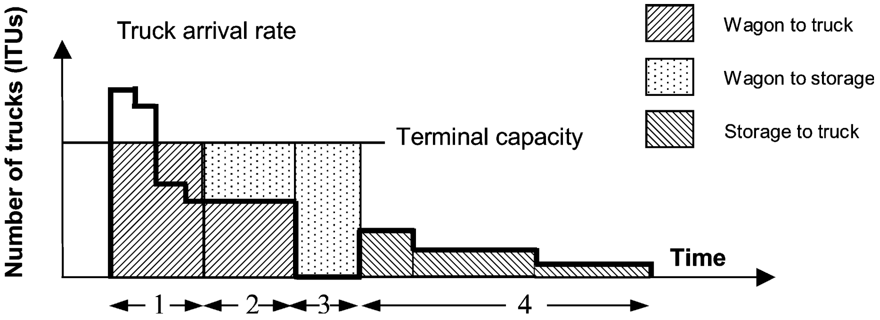

Fig. 2. Typical four crane phases of crane work.

wagon to store transhipment. This operation completes train unloading so that shunting operations or operations imposed by the floating system can be performed. In the fourth phase, the trucks are loaded indirectly from store (Bose, 1983).

This pattern applies to all rail terminals, but the duration of each phase differs significantly. Phases two, three and four are based on indirect transhipment and therefore require an intermediate storage area. The space requirements for this area are related to load unit volume and dwell time (of load units in phases two and three) and on the load unit type (size, stackable/non-stackable) and the maximum storage height of the handling equipment.

2.4. Type and number of handling equipment

2.4.1. Conventional handling equipment

A variety of handling equipment exists nowadays in the intermodal transport market, suitable for specific operating conditions. The handling equipment that are comparatively evaluated include a number of conventional as well as innovative technologies. The pre-selection phase for conventional handling equipment was based on discussions with experts (from Germany, Holland, France and Italy) in terminal design and operations. Reach stackers and rail-borne gantry cranes seem to dominate among conventional equipment.

Reach stackers are mobile cranes with a spreader attached at the edge of their boom. They are able to lift, handle, transport and stack ITUs. They serve trains, trucks and the storage area. Reach stackers are mainly used in small terminals due to the low cost and flexibility offered by this equipment. The vast majority (32 out of the 34) of Italian terminals are using reach stackers. The fact that they cannot stack very densely and require a great deal of space for manoeuvring significantly reduces their value for medium-volume and high-volume terminals. However, current practice at the Rail Service Center in Rotterdam indicates that an efficient pre-planning system (based on electronic data interchange) can increase the stacking density of reach stackers without significantly increasing ITUS re-shuffles.

Electrically operated rail-borne gantry cranes are currently the dominant equipment for high-volume combined transport terminals. This equipment came into regular use right at the early stages of the unified cargo method. These cranes straddle one or more railway lines, roads or rows of stored transfer units. They have a load-carrying capacity of 35 t and are equipped with a special arm for the handling of containers from top to bottom. The development and use of new types of load unit on the European market (swap bodies and semi-trailers) led to the modernisation of the handling equipment. The cranes were fitted with grapple-arms to permit the handling of the corresponding load units from underneath. Fig. 1 presents a representative gantry crane configuration (four transhipment tracks, three storage lanes, one driving and one loading truck lane). However, it is noted that many different gantry crane spans and track/lane configurations exist.

Straddle carriers and side loaders are not considered finally since they are proved to be more appropriate for maritime/barge than for rail/combined transport terminals. Gantry cranes on pneumatic tyres are also rejected on the basis of the experts' views who favoured reach-stackers and gantry cranes. Special low-volume technologies (e.g., self-loaded trucks, bimodal systems) are included in the analysis given that they are not widely adopted and cover only special cases in the European transport sector. Finally, terminal designs based on a combination of gantry cranes, reach stackers/fork lifts and multi-trailer transport devices (like the Rail Service Center terminal and the Europe Combined Terminals in Rotterdam) are also not considered because these technological solutions adopted, are strongly affected by the equipment configuration of the interrelated maritime terminal (for example, the multi-trailer system is mainly used for the harbour crane to storage area transfer operations) and therefore these solutions are not considered as "typical" in the European rail sector.

2.4.2. Advanced pilot handling equipment

A limited number of innovative technologies exist nowadays in Europe either in pilot form or in mature design phase (Fabel and Sarres, 1997). The common characteristic of all these technologies is that they offer fast handling as well as an advanced degree of automation. In order to achieve these goals, these new technologies incorporate one or more of the following ideas/techniques:

(a) Separation of rail side from roadside operations. This technique enables the optimisation of each sub-system and eliminates the conflicts between them. On the other hand, this separation creates the need for an intermediate internal transfer sub-system for the loading units or alternatively for a buffer with common access, without interference.

(b) The moving train technique where a special shunting locomotive moves the wagons in front of the handling equipment. This technique reduces the handling equipment travel time and enables fast automatic handling of the rail-side operations.

(c) Use of one complex crane spreader with many grapple arms or alternatively, many individual spreaders (each one with two grapple arms) hanging from a common overhead structure longitudinally to the transhipment rails. This technique enables the parallel handling of many loading units but on the other hand requires a high degree of automation and standardisation, both for the loading units and the wagons.

The choice of an innovative technology for consideration in the context of this analysis is based on two criteria: the existence of a pilot demonstration (that enables the evaluation of the technical performance of the equipment) and the availability of cost data (that enables the evaluation of the cost-effectiveness of the system). On the basis of these criteria, four technologies are considered. A common point of all these technologies is that the handling and storage operations are performed automatically, except for wagon pin adjustment and for truck service operation.

The first technological solution follows the (above mentioned) "moving train" technique. This technique is based on a high-speed rail transfer crane, a cross-conveyor system and a semi-automatic crane for the truck service and the storage operations. As the train moves slowly through the transhipment plant, the ITU position on the wagon and the identity and dimensions of the ITUs are identified by electronic sensors and the appropriate instructions are scheduled for the cranes.

The high-speed rail transfer crane (operates fully automatically) picks up the ITUs to/from the wagons and deposits them on the cross-conveyor system (and vice-versa). The cross-conveyor system comprises of self-propelling, individual pallets driven electro-mechanically. The ITUs are either transported directly to the semi-automatic crane or into the store. The store is managed automatically in that, a storage management program optimises the routes taken by the operating equipment and therefore prevents, as far as possible, any re-stacking procedures being necessary by taking into account train timetables.

Only one track exists under the crane area and only one train is processed at any given time. If it is not yet time for the train to leave, or if waiting is necessary for some other reason, the train must be placed in nearby sidings after processing in order to leave the track free for the processing of other trains.

The second technological solution is also making use of the of the "moving train" technique, the electronic sensors for the ITU identification and the store management system described above, but in this case one long span gantry crane serves all rail, road and storage activities. This solution enables also direct rail-to-rail transhipments since more than one track are placed below crane legs and some trains can be served in parallel. Additional siding is required for the remaining trains. The entire system is very compact, owing to the use of the above-mentioned "moving train" technique. The transhipment area length can be reduced to approx. 100–200 m or may be extended to achieve direct transhipment between two trains standing in parallel. A length of about 120 m is adequate to serve the German "Cargo Sprinter" rail vehicles. All trains exceeding the length of the transhipment area are served as they pass slowly through the transhipment area. This configuration allows a limited sequential and parallel hub-function to be offered in addition to the rail–road functions.

The third technological solution was originally designed for a hub railway station aiming at fast, fully automatic operation by using complex grapple arm spreaders. It is composed of unidirectional bridges perpendicular to the track for serving the rail side and a conventional gantry crane for the truck side. A cross-skid conveyor is used between the bridges and the truck gantry crane in order to link the rail- and roadsides, while allowing much better independent processing of the two types of equipment. A shuttle wagon is used for longitudinal movements from span to span. The train is processed in several stop positions, depending on the number of modules. One module for this approach is composed of five unidirectional bridges and is able to unload/load five wagons. This solution provides high flow rates and short train stopping times. Double stacking of load units is possible, both on handling tracks and under the crane on the truck side.

The fourth technological solution composes one complex grapple arm spreader mounted on a bidirectional rolling gantry crane that serves the rail side. In addition, a conventional gantry crane is used to serve the truck side. The complex spreader on the rail side can handle all the load units on a wagon in one single move. The gantry travels along the whole train, which means the train is processed in one single stop position. Double stacking of load units is possible on handling tracks and under the crane on the roadside. The link between the two gantries, on the rail side and on the lorry side, is direct, without cross-skid, via overlapping and interlocking between the moves of the two gantries. This approach reduces the investment required, but cross-skids could be added to enhance operation. Only one track exits under the crane area and only one train is processed at any given time. Nearby sidings accommodate the waiting trains.

2.5. Rail-side terminal access

Terminal access from the rail side is organised by the railways. Preferably, the terminal should be accessible from both ends, with trains entering from both directions. However, many existing terminals have dead-end tracks (only one access direction). Rail access is not usually electrified, a fact which implies a change to a diesel locomotive. However, this is required, as the loading tracks of the terminal cannot be electrified because the units are lifted by portal cranes or reach stackers and it is therefore impossible to install an overhead line. Two ways of improving this situation have been further analysed.

(a) Use a slewing catenary on the loading track. The railway line up to the transhipment area is also electrified so that the train can enter in the transhipment track by electric traction. Following the arrival of the train, the catenary withdrawal device is moved to one side (over the entire length of the train) and allows work to be carried out above the train in complete safety. The system yields significant time savings since the train can enter and leave the transhipment tracks without the need of a diesel and electric locomotive exchange.

(b) Allow the train to coast from the main line into position on the transhipment line with momentum. The railway line is electrified up to the transhipment area but not in the transhipment lanes (so there is no catenary over the length of the trains). The train enters the terminal with the pantograph lowered and stops when the electric locomotive is positioned under the overhead on the far side, so that it will be able to move off. Studies and a pilot demonstration have led the German Railways to conclude that the "coasting" technique is feasible. Following a trial phase, such a system was introduced at München-Riem in 1994. However, some specialists expressed doubts as to whether this rollingin speed could be achieved in all terminals. The alignment of the access track (in some French terminals for example) imposes significant limitations, while high winds could also pose problems. Another disadvantage is that the system requires a terminal with separate entry and exit tracks, otherwise the electric locomotive will be stuck in the transhipment area dead end.

2.6. Mean stacking height

ITU stacking reduces storage requirements and mean travel distance (for mobile handling equipment) or gantry span (for gantry configurations where the storage area is located between the gantry legs). On the other hand, ITU stacking increases handling activities, since it generates a number of shuffles (rearrangements required in order to provide access to the ITUs that are not on top of the stacks).

Containers are stackable while semi-trailers are not. Swap bodies manufactured to current European standards are not stackable. Trade experts and standardisation committee members are convinced that the market requires a new series of stackable swap bodies (or European domestic containers), in addition to the current type of swap body. The design of such stackable swap bodies will reflect current ISO container features, and they will have top corner fittings. This would be an easy solution to any problem with moving such swap bodies stacked on board coastal ships.

Currently, the mean stacking height in the majority of rail terminals is slightly above one. Containers are usually stacked one or two high, while (exceptionally) an empty (box-type) swap body can be placed above a loaded one. This situation can certainly be improved on. Experience with maritime operations indicates that a mean stacking height of 1.5 can be achieved without significant time losses due to ITU shuffles, even with random pick-ups. As an absolute maximum, units can be stacked three high for storage-to-train activities but this requires an information-based system.

It should be noted that conventional gantry cranes have to leave a ground-to-spreader height of 9.9 m to allow a semi-trailer to pass over another semi-trailer on a pocket-wagon. This minimum crane height allows a stacking height of "2 + 1" in the storage area (two units stacked plus a pass through corridor one unit high).

It is also worth mentioning that there are technical solutions where ITU stacking is undesirable for operational reasons. As a sequence, some future terminals will probably operate with a low stacking height ratio.

3. The modelling approach

The modelling approach used for the comparative evaluation of the above conventional and advanced technologies is based on an expert system, a train/truck arrival generator, a terminal simulation module and a cost calculation module. The associated software was developed in Visual Basic while the cost calculation module in based on Excel logistic sheets.

The expert system offers alternative, "technically sound" terminal designs (amount and types of equipment, land requirements, mean stacking height, working hours, personnel requirements, etc.). Each of the proposed designs is then "examined" by the terminal simulation model which checks the equipment adequacy to serve all trains within their timetables and provides the cumulative distribution of the truck dwell time. Based on the above train and truck information the proposed design is accepted or rejected. A design is acceptable if all trains are served within their timetables and in addition, if the truck dwell times in the terminal comply with a quality of service criterion. In the present research, the quality of service criterion adopted imposes that "95% of the arriving trucks are served within 20 minutes". This criterion was used in EU research project (Ballis et al., 1997) and was confirmed by many terminal operators.

The elements of each "accepted" design (track length, road lane length, transhipment and storage area requirements, equipment type and number, supporting technologies, maintenance and personnel requirements), as well as the truck dwell times are "fed" into the cost calculation module which provide the associated "cost per ITU transhipped" value. Fig. 3 shows the methodology used to produce one cost-versus-volume point. The replication of the computational procedure for a series of cargo volumes produces a cost-versus-volume curve for the specific terminal configuration.

For each terminal design (produced by the expert system) a cost-versus-volume curve is produced. Each curve ends at the volume determined by the terminal capacity. This is imposed either by the inability of the handling equipment (see curve {a} in Fig. 3) to serve the trains within the timetable duration or the trucks within the quality-of-service criterion specified or by the track

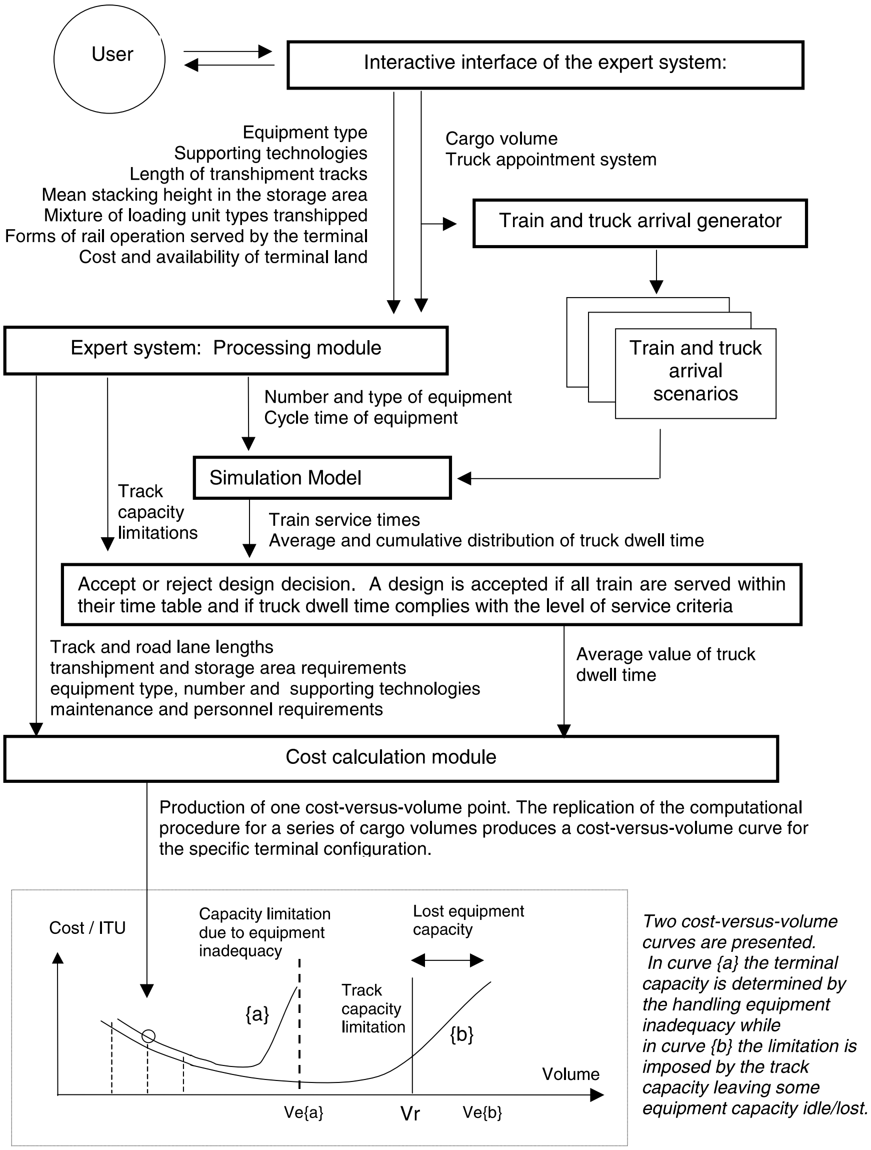

Fig. 3. Method used to produce cost-versus-volume curves.

capacity limitations (see curve {b}). In this later case and in order to theoretically analyse the terminal performance, the simulation ignores the capacity limitation imposed by the track capacity and continues so that the lost performance of the handling system is shown.

3.1. The expert system

An expert system is a computer program that attempts to imitate/emulate human expertise in terminal design. The expert system developed for this research consolidates parts of the experience and knowledge of experts, extracted out of a number of interviews and Delphi meetings with experts from the railways sector (European railways, terminal operators, technology providers) as well as with academics from the Transport field.

The expert system contains an interactive interface that assists the user to form "technically sound" terminal designs. Input parameters are allocated in two groups. The first group contains parameters that describe the terminal market and the operating conditions. These parameters are:

1. Cargo volume of the terminal.
2. Mixture of loading unit types transhipped.
3. Cost and availability of terminal land.
4. Forms of rail operation served by the terminal.

The second group of input parameters contains the terminal design parameters, namely:

1. Length of transhipment tracks.
2. Mean stacking height.
3. Equipment type.
4. Supporting technologies (also called "technological bricks") that include equipment add-on devices (anti-sway systems, semi-automatic control, positioning devices) and/or terminal supporting technologies (identification and location systems, information systems for terminal pre-planning, advanced terminal access systems).
5. Truck appointment system.

While the user enters the input parameters, the interactive interface "suggests" or "warns" for the use of proper equipment, add-on devices or supporting technologies, "rejecting" at the same time other selections. For example, specific cargo volume, ITU mixture, and cost of land combinations leads to "suggestions" for proper equipment types. A short "track length" selection leads to a "warning" that the use of advanced rail access systems have limited or no effects on train dwell time. An "equipment type" selection imposes the maximum value for the "mean stacking height" parameter. The selection of a rail access system "excludes" the use of similar systems to avoid double cost counting.

The expert system "compiles" each of the above "technological bricks" in terms of "compatibility", "performance" and "cost" attributes. The "compatibility" and the "performance attributes" – through an interactive interface – enable the user to form technically sound terminal designs. Moreover, the "performance" attributes participate in the calculation of the equipment service cycle, enabling the quantification of the contribution of each "technological brick" in the overall terminal performance.

3.2. The train/truck arrival generator

A "train arrival scenario" – which includes train arrival times, number of ITUS to be loaded/unloaded and train departure times – is adopted each time the simulation program is run.

The procedure begins with an "initial" train arrival scenario. The generator includes a number of "initial" train arrival patterns that were taken from real data observed in the Rotterdam–

Duisburg corridor for three categories: small, medium and large terminals. These train arrival patterns are rather conventional with the majority of trains arriving during the morning and leaving in the evening. Additional train arrival scenarios were created to cover the arrival rates between the three categories considered as well as rates lower than those for small terminals.

For each train arrival scenario, a non-stationary Poisson process is used to generate the associated truck arrivals. The pattern of the mean truck arrival rates is determined on the basis of corresponding empirical data. Two empirical patterns (following the German experience) are adopted for trucks arriving to pick up ITUs. The first corresponds to train arrivals between 9:00 (terminal opening hour) and 15:00 and the second for arrivals between 15:00 and 22:00 (terminal closing time). As far as truck arrivals for deliveries of ITUS are concerned, a third empirical pattern (also following the German experience) is considered for trains arriving at any time between 9:00 and 22:00. Since the simulation technique requires many replications, a significant number of truck arrival scenarios were carried out using different random number strings for the truck arrival times.

3.3. The simulation model

The model simulates both the rail side and the roadside of the terminal. In the rail-side part of the model, the arriving trains are entering the transhipment tracks. If these tracks are occupied, the trains enter siding/waiting tracks and wait for an empty transhipment track.

The train handling activities are simulated by the roadside part of the model together with the storage and truck handling activities. Fig. 4 presents the activities simulated in the roadside part of the model.

The performance of the truck service sub-system is strongly affected by the number and capabilities of the handling equipment as well as by the terminal operating conditions. The terminal

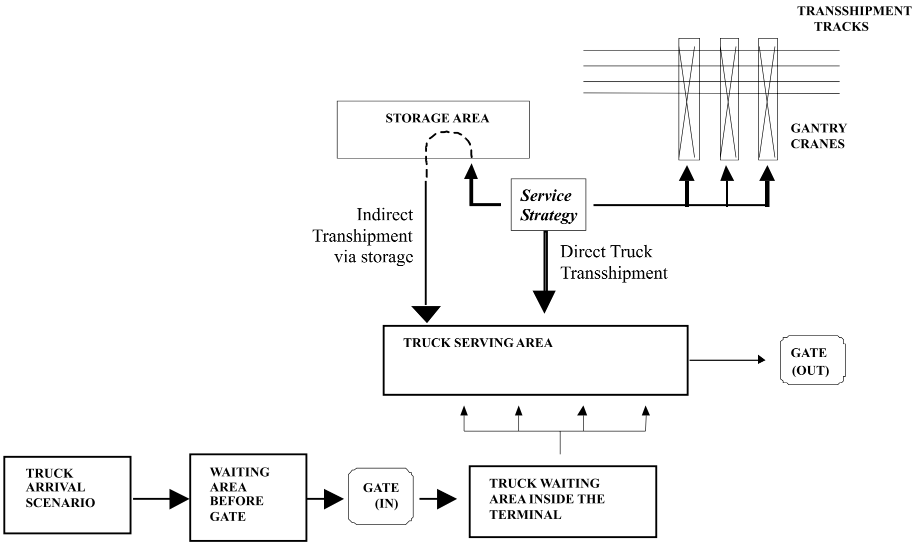

Fig. 4. Simulated activities in the roadside part of a model.

operating conditions that are taken into account in the simulation are the terminal working hours, the equipment service discipline, the truck arrival patterns and the synchronisation of the truck arrivals with the terminal operations. For this later condition, two cases were considered:

1. Terminal operation with a truck arrival pattern "adjusted to train arrival" (or the terminal opening hours if the train arrives during the night). This is the typical pattern in today's terminals and schedules. When the terminal operates under static capacity (see Section 2.2), all trains are standing in transhipment tracks and therefore all ITUs are available all the time. On the contrary, when the terminal operates under dynamic capacity form, train switch operations are needed that lead to "clear the train" operations in parallel to truck service operations. As a result, the truck dwell times are increased.
2. Terminal operation with a truck arrival pattern "adjusted to ITU availability". This means that the terminal should pre-plan and announce the period when the trains will enter the transhipment area (and therefore the ITU will be available) so that the terminal visits of the relevant trucks can be programmed accordingly. Alternatively, the terminal and the truckers must be synchronised using a "visit by appointment" system that enables the terminal to organise the pre- and on-carriage operations accordingly.

The truck delays considered were calculated by simulation. The "simulated" discipline initially gives train-to-truck priority over the train-to-storage transhipments. On the contrary, 2 h before the programmed switch of the trains (from the transhipment to the waiting tracks), focus is given to train-to-storage transhipments in order to ensure that the "clear the train" operation will finish on time. This discipline rule is an approximation sufficient for the equipment comparison purposes while it should be noted that the organisational and discipline rules in a real terminal are more complicated.

3.4. The cost calculation module

The question of costs in combined transport has always been a "grey" area. There is no universally accepted cost methodology in the railway sector and very little information is available in relation to the breakdown of operating costs. In many cases the rail prices include large overheads, internal cross-subsidies or are determined according to the highest price that the market can bear (Cantos et al., 1999). Furthermore, no cost data exists for terminals operating on the basis of pilot technologies.

For this reason, a "custom-made" cost calculation scheme has been particularly developed with the aim of comparing the cost-effectiveness of different alternatives. This cost scheme incorporates the following elements:

(a) Infrastructure (land acquisition, track formation, rail tracks, switches and signals, crane track, road lanes, gates, buildings, lighting, fencing, etc.) as well as handling and other terminal equipment. The annual cost for these elements was based in an amortisation periods of 30 years for the land and the civil engineering works and 20 years for the various terminal installations and equipment. The interest rate was assumed to be 7% for the whole amortisation period, an assumption based on experts' opinion (EC/DG Transport, 1999a).

(b) Maintenance and power.

(c) Personnel for the pure terminal operations. The personnel requirements for each system are calculated according to the terminal volume. It was assumed that this personnel also adjusts/locks the wagon pins (which is related to "handling"), but does not carry out the "inspection" work because this work is related to "train operation" and the corresponding cost is calculated separately.

(d) Train access procedures (from main line to terminal sidings) as well as rolling stock and cargo "inspection" (brake tests, cargo tests, etc). The costs for these procedures are determined according to access and handling procedures associated with the simulated technological solution.

(e) Cost of truck service time in the terminal. It is calculated taking into account the mean truck dwell time in the terminal (average of the simulation replications) multiplied by 37.5 Euros/h. This rate is based on the outcome of a relevant study performed by Eidgenossische Technische Hochscule Zurich, which examines various truck operating schemes (EC/DG Transport, 1999b). Of course, any other rate can be used.

The cost of train time is not taken into account in the terminal cost due to the fact that the train dwell time is predetermined (by the train arrival and departure timetables). The simulation checks if the specific terminal configuration can serve the train within the time-window defined by the train arrival and departure times. The benefits from a shorter train dwell time in the terminal are related to the rail operating schemes. The macro-model (mentioned in Section 1) can be used for a similar analysis concerning the total combined transport chain. This was carried out for the Rotterdam–Duisburg corridor (EC/DG Transport, 1999b) but this part of the work is outside the context of the current presentation.

4. Results and findings

Rail–road terminals are parts of the intermodal transport chain. Parameters like the terminal's location in relation to the spatial allocation of production and consumption centres, the existence of antagonistic terminals, the access to the major rail and road networks, the cost and availability of land significantly affect the terminal size and performance. However, a number of parameters are determined by the terminal planner (or imposed by the terminal authorities) and play a dominant role since the parameters outline the terminal layout and determine its limits and productivity. Within the current research, alternative conventional and innovative equipment configurations are comparatively evaluated by use of a modelling tool (expert system, simulation, cost module). There are two groups of results associated with the above analysis.

4.1. Land requirements and number of equipment needed

The first group concerns the comparison between conventional and advanced technologies in terms of land requirements and number of equipment needed. This comparative evaluation reveals some similarities as well as some distinct differences.

The layouts of the advanced handling designs are relatively flexible since the transhipment module can be separated from the siding module in any nearby “convenient” location, or existing sidings can be used. The transhipment area can be arranged in a rectangle. Compared with the “conventional” shape (long rectangle with a length equal to that of the transhipment lane), this layout reduces the transport distance as well as the internal road network, thus leading to area savings. In addition the computer-based management of the storage area (offered by the advanced designs) optimises the routes taken by the operating equipment and therefore minimises re-stacking procedures as far as possible.

As regards ITUS stacking, the advanced systems follow different approaches from the conventional. Conventional systems use the wagons as temporary storage points (and therefore indirect handling and stacking areas). Advanced systems free wagons as far as possible (allowing better rolling stock utilisation) and create some additional intermediate storage/buffer requirements, which are partly offset by advanced storage management systems.

On the contrary, there are no great differences in the total (transhipment and siding) number of tracks between conventional terminals and advanced terminals (and consequently the associate area requirements). However, it should be noted that the advanced design is more flexible since the transhipment can be separated from the waiting tracks and can be located in any “convenient” area.

Distinct differences exist in the number of equipment required for advanced and conventional configurations that offer almost the same ITU throughput. Less handling equipment is required for the advanced configurations in relation to conventional solutions.

Simulation results show that a limited number of fast “servers” gives better service times than a larger number of slow “servers”. From the operating point of view, there are also cost savings due to reduction in personnel. On the other hand, special care must be taken to ensure uninterrupted operation of the (fewer) fast handling equipment since a breakdown has quite significant effects on service system output.

4.2. Competitive evaluation in terms of cost

The second group of results concerns the comparative evaluation of mutual competitive configurations (conventional versus advanced but also conventional versus (other) conventional) in terms of cost.

Fig. 5 shows the overall outcome of the modelling and cost calculation procedure, namely the cost-versus-volume curves. Each curve is associated to a technological solution and to specific train/truck synchronisation technique (truck arrivals adjusted to train arrival or to ITU availability). Three types of conventional gantry cranes having different basic handling rates (22, 24 and 28 ITUs/h) and purchase costs are used. All terminals were designed with dynamic capacity capabilities. These curves enable the identification of the limitations for each terminal design as well as the cargo volume range where each technology seems to be cost-effective.

The cost figures include infrastructure, equipment, maintenance, energy, personnel and truck waiting time costs. They do not include advanced direct access systems/techniques (slewing catenary, coast with momentum). Both techniques require complicated installations on site, such as signalling of transhipment tracks, electrified switches and overhead junction crossings. Both

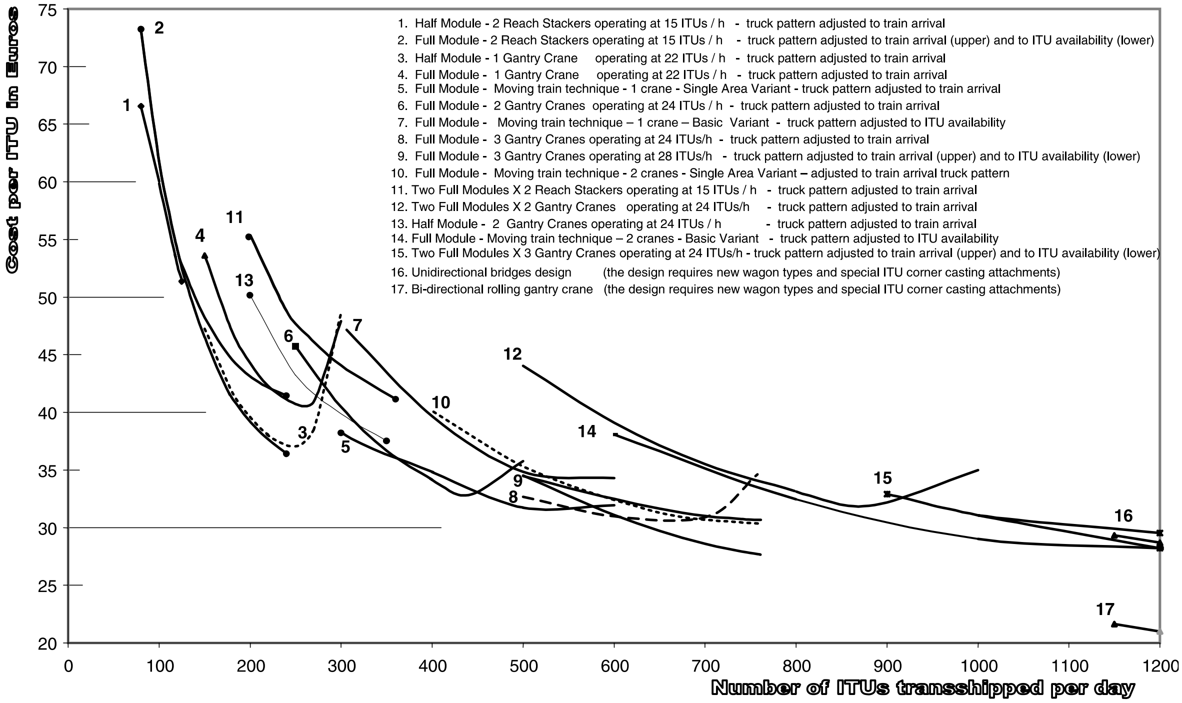

Fig. 5. Comparative cost analysis for alternative terminal designs (includes infrastructure, personnel and truck times).

techniques can be applied to conventional as well as to advanced technical solutions. Their effects are more significant for the network (rail operating forms that require limited dwell time per train stop) than for the terminal operation. For this reason, their cost effects are analysed elsewhere (EC/DG Transport, 1999a).

The cost-versus-volume curves shown cover a traffic volume that ranges from 150 to 1200 ITUs/day. Each curve ends when the dynamic terminal capacity is exhausted either due to equipment inadequacy (these cases can be easily identified by their characteristic "U" shape) or due to track capacity limitations.

The logical step to overcome a terminal limitation imposed by equipment inadequacy is to increase the number of handling equipment, or to use add-on devices (semi-automatic control, anti-sway systems, etc.) that improve existing equipment productivity or even to use faster equipment types. However, certain inconveniences seem to arise. Each additional equipment creates operational conflicts, so that usually no more than three equipments exist in one module. Some existing equipment types cannot accept add-on devices without extensive modification. The faster equipment has its own maintenance requirements (parts and knowledge). And of course all this improvement creates additional investment, maintenance and (in case of additional handling equipment) labour costs.

On the other hand, the terminal limitations imposed by the track capacity limitations cannot be easily overcome. When a terminal is designed for static capacity, it can be converted for dynamic capacity by adding a certain number of siding/waiting tracks. For operational reasons the number of the above additional tracks, usually cannot be more than 50% of the number of transhipment tracks (of equivalent length). The total number of transhipment and siding/waiting tracks defines the terminal's dynamic capacity. When the terminal exhausts this dynamic capacity, an extra module (track and equipment) should be added to increase the terminal capacity that generates a peak to the terminal cost.

Alternatively, a better track utilisation can expand terminal capacity above today's limits (e.g., the 750 ITUs/day for the conventional gantry-based system) without the need for second module but that requires advanced (fast liner trains, overnight shuttle–shuttle operations, fast hub and spokes, etc.) rail operating forms.

The cost curves are drawn using specific assumptions as regards schedules, truck arrival pattern, technologies, performances and detailed costs to enable a very good internal comparison of different terminal designs and technologies. An overview of the curves in Fig. 5 indicates that relatively high costs are related as expected to low volumes (irrespective of the equipment technologies). These costs decrease as volumes increase but an asymptotic trend is observed at the level of 30 Euros/ITU. However, comparison with a "real-life" situation might lead to astonishing results. The calculated costs are double the "price" accepted by the market. This is explained by the fact that the model takes into account the investment cost that accounts for about 50% of the total terminal cost. This means that under today's pricing system, the terminal covers only its operating cost.

Further computation was also performed to expand the cost-versus-volume curves beyond the limits imposed by the track capacity (not shown in the figure to avoid confusion) in order to identify the idle capacity of the handling equipment. This analysis revealed that many terminal configurations have significant equipment idle capacity, which could lead to lower cost/ITU values if not restricted by the track limitation.

More alternative choices exist for medium-sized and large terminals (more than 350 ITUs/day), whereas small terminals are dominated by conventional technologies. Half-module terminal configurations seem to be more economical than the full modules using the same handling equipment, for the low- and low to medium volume ranges. This explains why many (even newly developed) existing terminals have short (450–550 m) transhipment tracks. The comparison of the infrastructure cost for a long transhipment area with that for a shorter transhipment area plus the additional operating cost for servicing the train in two parts favours the latter. This fact has more global effects since these "lower cost" terminal configurations increase the train dwell time in the terminal also for liner and feeder trains and therefore restrict the implementation of new rail operating forms that could bring benefits for the combined transport chain.

The bottom line of this research is that each design is effective for a certain cargo volume range and is restricted by its capacity limitations. The terminal's capacity limitations are imposed mainly by the capacity limitations of the sidings/transhipment track sub-system rather than by the handling equipment given that there are technical solutions to provide the required support for the handling operations. It is also rather clear that advanced technological solutions should be coupled with "advanced" rail operating forms and proper truck booking systems. The advanced operating forms (liner trains, hub and spoke and overnight shuttle form) instead of today's practice (trains travelling during the night and served during the day) permit the effective use of the time saving due to fast handling. In addition, the adoption of efficient booking systems could lead to truck arrival patterns "adjusted to ITU availability" which reduce the indirect transhipment movements in comparison to those of the currently used "adjusted to train arrival" truck patterns.

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